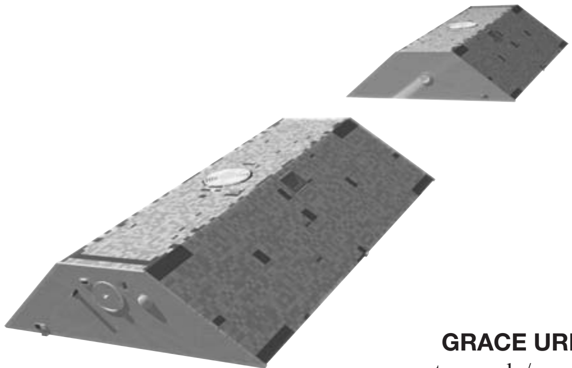
GRACE

Gravity Recovery and Climate Experiment



GRACE URL
www.csr.utexas.edu/grace

Summary

The GRACE mission enables the most precise measurements of Earth's mean and time-variable gravity field ever obtained and should lead to advances in the fields of hydrology (continental and regional water balance, monitoring changes in aquifers), oceanography (studying ocean currents, ocean heat flux, ocean bottom pressure, sea-level rise), and solid-Earth sciences.

Instruments

- Black-Jack Global Positioning System Receiver (GPS)
- High Accuracy Inter-satellite Ranging System (HAIRS)
- Star Camera Assembly (SCA)
- SuperStar Accelerometer (SSA)
- Ultra Stable Oscillator (USO)

Note: Unlike most missions, the twin GRACE satellites are not platforms for independent remote-sensing instruments. Instead, the satellites themselves act in unison as the primary science instrument. Listed here as 'instruments' are the components needed to make gravity measurements.

Points of Contact

- *GRACE Principal Investigator:* Byron Tapley, University of Texas Center for Space Research (UTCSR)
- *GRACE German Co-Principal Investigator:* Christoph Reigber, GeoForschungsZentrum Potsdam (GFZ)
- *GRACE Project Scientist:* Michael M. Watkins, NASA Jet Propulsion Laboratory/California Institute of Technology

Key GRACE Facts

Joint with Germany

Heritage: Challenging Minisatellite Payload (CHAMP)

Platform: Carbon fiber reinforced plastic layered aluminum honeycomb main equipment panel for µm-level dimensional stability

Orbit:

Type: 500 km near-circular polar orbit at launch, w/220 ± 50 km separation between the satellites
Altitude: 500 km
Inclination: 89°
Period: 94.417 minutes at launch
Repeat Cycle: None, track evolves naturally

Dimensions: Twin trapezoid satellites, 3.1 m × 0.8 m × (1.9–0.7) m each

Mass: Each satellite weighs 460 kg

Power: 160 W (94 W payload and s/c; 56 W heaters)

Fuel: 34 kg GN2 propellent for attitude control and station-keeping

Design Life: Planned five-year mission

Average Data Rate: 1 Mbps

Data Relay Methods: Weilheim & Neustrelitz stations—German Space Operations Center (GSOC)

Downlink: S-Band

Transmission Frequency: 24 and 32 GHz for K-Band ranging

Thermal Control: 0.1° C on critical components

Attitude Control: Star sensor, Gyro, Magnetometer, Mag-torquer, GN2 thrusters

Pointing: 3–5 mrad dead-band pointing of K-band horn to other GRACE satellite

Accuracy of Calibrations:

K-Band Horn Alignment: Known to within 0.02° of Star Camera

Accelerometer Alignment: Known to within 0.03° of Star Camera

Satellite Center of Gravity: Measured and actively trimmed to within 20–40 µm of the center of the accelerometer

Other Key Personnel

- *GRACE Program Scientist:* John LaBrecque, NASA Headquarters
- *GRACE Program Executive:* Lou Schuster, NASA Headquarters
- *GRACE Project Manager:* Joseph Beerer, NASA Jet Propulsion Laboratory/California Institute of Technology

Mission Type

Earth Observing System (EOS) Exploratory Mission (Earth System Science Pathfinder)

Launch

- *Date and Location:* March 17, 2002, from Plesetsk Cosmodrome, Russia
- *Vehicle:* Rockot launch vehicle

Relevant Science Focus Areas

(see NASA's Earth Science Program section)

- Climate Variability and Change
- Earth Surface and Interior
- Water and Energy Cycles

Related Applications

(see Applied Sciences Program section)

- Disaster Management
- Water Management

GRACE Science Goals

- *Primary goal:* Provide global, high-resolution estimates of the constant and time-variable part of Earth's gravity field, with unprecedented accuracy.
- *Secondary goal:* Measure several hundred global atmospheric profiles per day to determine how GPS measurements are distorted by Earth's atmosphere and ionosphere.

Background

Measurements of Earth's gravity field provide integral constraints on the distribution of mass within the Earth system. A record of time variations in Earth's gravity field reflects the exchange of mass (primarily from moving water) within the land, ocean, and atmosphere components of the Earth system. Such records serve as important global constraints on the models of variability and exchange within and between each sub-system. The mean Earth

Key GRACE Facts *(cont.)*

Satellite Subsystems

Responsible Center: NASA JPL

Satellite System: Astrium Space (Germany)

Attitude Control System: Space Systems/Loral (U.S.)

Instrument Subsystems

Responsible Center: NASA JPL

GPS: NASA JPL

HAIRS: NASA JPL

Microwave Assembly: Space Systems/Loral (U.S.)

Star Cameras: Danmarks Tekniske Universitet (Technical University of Denmark)

SuperStar Accelerometer: Office National d'Etudes et de Recherches Aerospatiale (ONERA) (France)

Ultra Stable Oscillator: Applied Physics Laboratory (Johns Hopkins University) (U.S.)

Launch & Ground Operations

Responsible Center: Deutches Zentrum für Luft und Raumfahrt (DLR) (Germany)

Launcher Subsystem: Eurockot GmbH (Germany)

Mission Operations: German Space Operations Center (GSOC)

Science Data System

Responsible Centers: UTCSR, NASA JPL, GFZ gravity field, on the other hand, provides constraints on the composition and structure of the Earth. In addition, over the oceans, it provides the reference surface relative to which ocean topography variations and ocean currents and their changes may be reckoned. Precise gravity field measurements, therefore, in conjunction with other satellite and in situ measurements, underpin a large variety of climate-change-related studies in oceanography, hydrology, glaciology, and solid-Earth sciences (see NRC 1997 for a survey of applications).

Past determinations of Earth's gravity field have used a combination of multi-decadal records of space-based satellite tracking data as well as land and marine gravity measurements. The satellite tracking data have contributed primarily to the determination of the long- and medium-wavelength static gravity field—whereas terrestrial data have determined the medium and short wavelengths. Determinations of the variability of Earth's gravity field however, have been limited in the past to only the very longest wavelengths—a combination of lack of coverage as well as limited precision of tracking. For these reasons, the need for global, high-resolution and accurate measurements of Earth's gravity field for Earth system science has long been articulated.

GRACE is a joint NASA-DLR Earth gravity-field-mapping mission, implemented under the Earth System Science Pathfinder Program starting in 1997. The change in distance between the twin co-orbiting GRACE satellites (popularly named Tom and Jerry) is used, along with ancillary data, to monitor the mean and time-variable gravity field of Earth.

Using the GRACE Satellites as an Instrument to Measure Gravity

With the GRACE mission, the spatio-temporal variations of Earth's gravity field are traced by a sequence of estimates of the spherical harmonic coefficients of the geopotential model. While Earth's gravity has a continuum spectrum of variability, for reasons of limitations of ground-track-coverage density, this spectrum is represented by a set of monthly piece-wise constant estimates of the parameters of the Earth gravity model. The monthly gravity-field estimate is obtained from a continuous record of change in the distance between the twin GRACE satellites.

Spatial and temporal variations in Earth's gravity field affect the orbits (or trajectories) of the twin spacecraft slightly differently. These differences are manifested as changes in distance between the spacecraft as they orbit Earth. This change in distance is reflected in the change in time-of-flight of microwave signals transmitted and received nearly simultaneously between the two spacecraft. While this differential orbital motion is considerably smaller than the gross motion of any one satellite, having a pair of co-orbiting satellites makes it possible to measure continuously and with high precision, these minute changes in distances. Designed at JPL, the High Accuracy Inter-satellite Ranging System (HAIRS) provides this distance change as phase change of the microwave carrier signals. Measurements are made at 24 and 32 GHz to correct for the ionospheric effects on the signal. The dual one-way range (or its numerical derivatives) can be reconstructed from these phase

GRACE Instruments

GPS
Global Positioning System

Provides digital signal processing; measures the change in distance relative to the GPS satellite constellation.

HAIRS
High Accuracy Inter-satellite Ranging System

K-band microwave ranging system that provides precise (within 10 μm) measurements of the change in distance between the two satellites—these measurements are used to infer changes in gravity.

SCA
Star Camera Assembly

Precisely determines satellite orientation by tracking the satellite relative to the position of the stars.

SSA
SuperStar Accelerometer

Precisely measures the non-gravitational accelerations acting on the satellite.

USO
Ultra Stable Oscillator

Provides frequency generation for the K-band ranging system.

data using precise relative timing between the satellites obtained from simultaneous GPS tracking data. Precision of such distance-change measurements is a few µm, over a nominal separation distance of 220 km.

Since the range change depends not only on the gravity field, but also on non-gravitational force variations, each satellite carries the SuperSTAR Accelerometer (SSA). Built by ONERA (France), this accelerometer uses the principle of electrostatic levitation to suspend a proof-mass within an electrostatic cage. The cage itself is rigidly attached to the GRACE spacecraft and is affected by the skin forces acting on the satellite. The proof-mass is located at the center of gravity of the spacecraft and is in free-fall so that non-conservative forces cause the distance between the proof-mass and the electrode cage to change continuously. This distance is measured using capacitive sensors and is used to derive the control forces necessary to keep the proof-mass centered within the cage. These control forces are therefore a measure of the non-gravitational forces acting on the satellite.

The GRACE satellites also carry a geodetic quality, BlackJack GPS receiver, which provides the precise relative and absolute timing for the data, as well as the absolute position of the spacecraft. The dual star cameras (SCA) are used to obtain the precise orientation of the spacecraft, in particular for the accelerometer and the K-Band boresight.

Unlike most remote-sensing-instrument suites or missions, the science product from the GRACE mission itself is not a sequence of quasi-instantaneous and independent images of Earth. The GRACE products are not a sequence of images or time slices of a particular process or state variable, but rather continuous records of the time history of the motion of the twin satellites. The suite of GRACE satellite measurements—primarily the range change, the non-gravitational acceleration vector, and the precise pointing – is collected over a suitably large span of time. This is to ensure sufficient density of data coverage either globally or regionally. For global models, sufficient density of coverage— required to support determination of gravity fields to a few 100 km resolution—is obtained in approximately one month. This data set is then used in conjunction with a variety of ancillary data to provide an estimate of the average state of Earth's gravity field over that month.

The GRACE products are defined to be the coefficients of a spherical harmonic model of Earth's gravity field. Each month, a set of harmonics complete to degree and order 100 is reported (approximately 400-km effective wavelength). In addition, a long-term mean to degree and order 160 is to be provided.

Using GRACE GPS Receivers as Atmospheric Limb Sounders

Although GRACE is primarily an experiment to measure gravity, the extremely precise GPS receivers onboard can also be used as atmospheric limb sounders. Limb sounding involves scanning across the atmosphere (called Earth's limb) and can be used to measure how much a radio wave (a GPS signal) is distorted as it travels through Earth's atmosphere and ionosphere. (This is analogous to what happens to a beam of light when it passes through water.) The precise degree of bending depends on the atmospheric conditions—pressure, temperature, and moisture content—and on the density of electrons in the ionosphere.

Distortions caused by the atmosphere remain constant with changing radio frequencies but ionospheric distortions vary depending on the radio frequencies. So, by varying the radio frequency, it is possible to distinguish how much of the distortion is caused by the atmosphere and how much is caused by the ionosphere. So using this technique, it is possible to ascertain profiles of pressure, temperature, and humidity for the atmosphere and also to measure the variability of electron density in the ionosphere.

The limb technology on GRACE extends and complements other spaceborne atmospheric sensors. GRACE will provide about 500 limb sounding measurements per day, unaffected by weather conditions (such as clouds and storms) that hinder or block other satellite sensors. The GRACE limb sounding measurements will help determine the effectiveness of limb sounding as a cost effective means of improving numerical weather prediction. It will also help to advance our understanding of the Sun's influence upon Earth's environment, including its effects on climate, weather, radar, and radio communications. Limb sounding will also be studied as a means of detecting rapid vertical changes of Earth's surface such as volcanic explosions, earthquakes, tsunamis, and other such phenomena, which are thought to cause disturbances in the ionosphere.

Data Products

The Science Data System is responsible for system development, data processing, and archiving. The GRACE Raw Data Center (RDC) at DLR in Neustrelitz, Germany receives the telemetry data. NASA JPL handles Level 1 data processing, where sensor calibration factors are applied, the data are correctly time-tagged, quality control flags are added, and the data sample rate is reduced from the high rate data of previous levels. Data are then sent to UTCSR and GFZ, where the mean and time variable gravity field is derived from calibrated and validated data. Data are archived for distribution at JPL's Physical Oceanography Distributed Active Archive Center (PO.DAAC) and at GFZ's Information System and Data Center (ISDC). GRACE data include 30-day estimates of gravity fields, as well as profiles of air mass, density, pressure, temperature, water vapor, and ionospheric electron current.

GRACE References

Dunn, C. E., and 19 others, 2003: Instrument of GRACE: GPS augments gravity measurements, application challenge. *GPS World*, **14 (2)**, 16–28.

National Research Council, 1997: *Satellite Gravity and the Geosphere: Contributions to the Study of the Solid Earth and Its Fluid Envelope*, National Academy Press, Washington D.C.

Tapley, B. D., S. Bettadpur, J. C. Ries, P. F. Thompson, M. Watkins, 2004: GRACE measurements of mass variability in the Earth system. *Science*, **305**, 503–505.

Tapley, B. D., S. Bettadpur, M. M. Watkins, and C. Reigber, 2004: The Gravity Recovery And Climate Experiment: Mission overview and early results. *Geophys. Res. Lett.*, **31**, L09607, doi:10.1029/2004GL019920.

Tapley, B. D., S. Bettadpur, M. Cheng, D. Hudson, and G. Kruizinga, 2003: Early results from the Gravity Recovery And Climate Experiment. Paper AAS-03-622, AAS/AIAA Astrodynamics Specialists Conference, Big Sky, Montana.

Watkins, M. M., and S. Bettadpur, 2000: The GRACE Mission: Challenges of using micron-level satellite-to-satellite ranging to measure the Earth's gravity field. *Proc. Internat. Symposium on Space Dynamics*, Biarritz, France 26–30 June 2000, Centre national D'Etudes Spatiales (CNES), Delegation a la Communication.

Watkins, M. M., E. S. Davis, W. G. Melbourne, T. P. Yunck, J. Sharma, S. Bettadpur, and B. D. Tapley, 1995: GRACE: A new mission concept for high resolution gravity field mapping. *Proc. Euro. Geophys. Soc.*, Hamburg, Germany.

GRACE Data Products

Product Name or Grouping	Processing Level	Coverage	Spatial/Temporal Characteristics
GRACE *Data Set Start Date: April 14, 2002*			
Intersatellite Range (and Derivatives)	1B	Continuous	5 s
Non-Gravitational Accelerations	1B	Continuous	1 s
Attitude (Quaternions)	1B	Continuous	5 s
GPS Tracking	1B	Continuous (L1/L2, P1/P2 & CA)	1–10 s
Monthly Geopotential	2	Global (~30 days)	Harmonic degree 100 (max)
Mean Geopotential	2	Global (lifetime)	Harmonic degree 160 (max)

Notes:

Level 1B Products are the processed range and acceleration measurements, which are input to Level 2 processing while creating the gravity field.

Level 2 Products are monthly models for the Earth gravity field (derived from Level 1B data products and ancillary data).

L1/L2 refers to the phase at the two GPS frequencies; P1/P2 refers to the precise (P) code tracking; CA is an acronym for Coarse-Acquisition code tracking.

GRACE Data Products